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Fundamentals of Geology and Seismology for Earthquake Engineers

(Seminar No. 4)

Organizer:

W. W. Hays

Specialty Seminars on Earthquake Engineering

held at

Stanford University

Stanford, California

July 17, 1984

Publication No. 84-06

Earthquake Engineering Research Institute

EERI

FORMULATING EARTHQUAKE RESISTANT DESIGN CRITERIA*

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INTRODUCTION

The primary function of design criteria in general, and earthquake-resistant design criteria in particular, is to restate a complex problem that has unknowns and uncertainties into an unambiguous, simplified form having no uncertainties. The design criteria should provide clearly stated guidelines for the designers. For example, when actually designing a structure, an engineer needs to know the forces and deformations that the structure should be able to resist. Some of these forces, such as dead loads imposed by gravity, are well known, but others that result from transient actions of nature or man, such as earthquake, wind or live loads, are not known. This lack of knowledge must somehow be circumvented and a precise, unambiguous statement of the design conditions must be given to the design engineer. This is accomplished by means of the design criteria. The designer also needs to know the properties of the materials and structural elements that will be used, but as these are not precisely known, mainly because of imperfections in materials and workmanship, the design criteria must also take this into account. In the preparation of the design criteria, allowance must be made for the uncertainties, and it is necessary to be cognizant of all the unknowns for which allowances must be made.

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* This presented is abstracted, with modifications, from the EERI Monograph "Earthquake Design Criteria" by G.W. Housner and P.C. Jennings

The traditional engineering design criteria, for example those in the Uniform Building Code, specify live loads that are greater than the actual loads typically encountered, and specify allowable design stresses that are appreciably less than the expected ultimate strength of the material. The purpose of this procedure is to ensure extra strength that is sufficient for unforeseen variations in loads, in material properties, and in workmanship. These criteria, in effect, tell the design engineer: "If you design according to these requirements, the structure will be considered adequate." A similar approach could be taken for earthquake-resistant design if the conditions were more or less the same for all projects. However, because the seismic hazard varies markedly from place to place and because structures and facilities vary in importance, cost, length of life, ease of repair, materials of construction and consequences of failure, the formulation of seismic design criteria for other than ordinary buildings cannot, in general, be codified simply; special knowledge and judgment are required for formulating the criteria.

THE USE OF SEISMOLOGICAL AND GEOLOGICAL DATA

When designing structures for a seismic region, what the engineer would really like to know is the strongest ground shaking that the site under consideration will experience during the life-time of the planned facility. This pre-knowledge, however, is not available, so recourse must be had to estimating what might happen in the future by studying what has happened in the past. Seismological and geological data form the basis for estimating future ground motions, including shaking and possible fault rupture, and studies for important facilities sited where the possibility of major earthquakes must be considered nearly always involve geologists and seismologists.

The seismic history of a region in the U.S. shows what has happened in the recent past, for example the last two hundred years, and thereby gives an indication of what might be expected in the next two hundred years. In a similar way, geological studies can give information on the occurrence of faulting and earthquakes over a longer time span, typically thousands or hundreds of thousands of years, and can thereby provide longer term estimates of the activity of faults than is available from the historical record alone. In this sense the past is used by the geologists and seismologists to predict the future. The correct use of the recommendations of geoscientists by earthquake engineers requires an understanding of the terminology and concepts used by scientists.

EARTHQUAKE MAGNITUDE

Any measurement that characterizes the size of the area of strong shaking, or the extent of the "felt area," or the total energy released in shaking, could serve as an indication of the size of the earthquake. As originally developed by C.F. Richter at the California Institute of Technology, the earthquake magnitude scale uses as the pertinent measurement the peak amplitude recorded by a standard Wood-Anderson seismograph, which has a natural period of 0.8 seconds, approximately 80% of critical damping and a magnification of 2800. The peak amplitude, A, of Wood-Anderson seismograms varies over the surface of ground in a manner similar to the variation of intensity of ground shaking, being very small at large distances from the fault and thousands of times larger close to the fault; so for a measure, the $\log_{10}A$ is used. The plot of

$\log_{10}A$ forms a hill-shaped surface and the volume of the hill would be a good measure of the size of an earthquake, but it would not be practical to evaluate. A less precise, but more practical, measure is that defined by Richter:

$$M_L = \log_{10}A - \log_{10}A_0(\Delta)$$

In this expression, M_L is the local magnitude, Δ is the epicentral distance in kilometers, and $A_0(\ )$ is the Wood-Anderson amplitude corresponding to an earthquake with magnitude zero. The variation of $A_0(\Delta)$ with distance was determined from data and the level was fixed by setting its value at 10^{-3} millimeters for a distance of 100 km. Two different seismographic stations will not, in general, compute the same value of M_L, and the "official" value is usually the weighted average from several records. Also, the magnification of the standard Wood-Anderson instrument and of almost all other seismographs is such that the instruments are driven off-scale by motion strong enough to be felt, so the use of seismographs to determine the magnitudes of larger earthquakes necessarily requires the readings to be made at large distances where the character of the ground motion is much different from that near the fault. At such distances, the motion does not contain direct information about the nature of the close-in, potentially destructive shaking.

Seismic waves change their character as they travel away from the causative fault. In particular, at larger distances the compression waves, shear waves and surface waves separate out and the nature of the waves also change. This has led to certain refinements in determining earthquake magnitudes, and other magnitude scales have come into use.

The most common of these are the surface-wave magnitude M_s, the body-wave magnitude M_b, and the moment magnitude M_w. In general, the different magnitude scales do not give the same numerical values, although they agree at some levels and there are empirical techniques for converting from one to another. At distances of a thousand kilometers and more, surface waves of 20-second period predominate in observed seismograms and the amplitude of this motion is used to determine M_s, which is the value most commonly reported in the press for major earthquakes. Earthquakes smaller than about $M_L = 6$ typically do not generate enough surface waves for a determination, so the M_s scale is designed to agree with M_L for magnitudes in the range of 6 to $6\frac{1}{2}$. For larger earthquakes the value of M_s consistently exceeds that of M_L. For example, the 1906 San Francisco earthquake had the approximate magnitudes $M_s \approx 8.3$ and $M_L \approx 6.9$. The largest observed local magnitudes are in the $7\text{-}7\frac{1}{4}$ range, whereas surface wave magnitudes as high as 8.6 have been assigned.

For the very largest earthquakes in history, such as the Chilean earthquake of 1960 and the Alaskan earthquake of 1964, the surface-wave magnitude "saturates" in the sense that it cannot well distinguish two very large events of different fault lengths on the basis of the maximum amplitude of the 20-sec surface waves. For this reason H. Kanamori developed the moment magnitude, M_W. This magnitude scale is based on the total elastic strain energy released by the fault rupture, and this is related to the seismic moment M_0 defined by

$$M_0 = \mu AD$$

in which μ is the modulus of rigidity of the rock, A is the area of the rupture surface of the fault and D is the average fault displacement. M_0 can be estimated from geological evidence which defines the area and extent of rupture, or from records of long period seismographs at large distances, for which even the largest earthquake appears to be a relatively short event. Because M_W and M_0 do not saturate and do measure all the energy released, even that at periods of tens and hundreds of seconds, they are of more fundamental scientific interest to seismologists than the local magnitude, M_L. The largest earthquake on the moment magnitude scale is the Chilean event of 1960 which had a fault length of approximately 600 miles and an assigned value of $M_W = 9.9$, compared to $M_S = 8.6$.

Having these different magnitudes introduces an element of confusion into earthquake engineering. The most commonly used magnitudes, as given in Gutenberg's and Richter's Seismicity of the Earth (Ref. 4) or in the U.S.G.S. publication United States Earthquakes (Ref. 15), are M_L for moderately large earthquakes (M = 6.4 for 1971 San Fernando) and M_s for large earthquakes (M = 8.4 for 1964 Alaska).

The consistent use of M in this way means that its value will convey an idea of the size of the event. Because practices vary, it is advisable to ascertain what magnitude scales are used in any presentation concerning magnitudes.

SEISMOGOLICAL DATA

Depending on the region, seismological data are available in various amounts and degrees of quality. There are countries with some form of seismic record going back as much as two or three thousand years, while the historical record in the western United States is seldom as long as two hundred years. Instrumental seismology has, of course, a much shorter history with a maximum of about one hundred years. Similarly, there are some regions having networks of seismic instruments sufficiently good to record all perceptible shocks and to determine their locations to within a few kilometers; however, most seismic regions have much less extensive coverage. Seismological data of high quality imply instrumentally determined magnitudes and epicenters of all significant events, with locations accurate enough to correlate earthquakes with geologic features of the region. Earthquake data must include a sufficiently large number of events so that enough earthquakes of larger magnitudes are present to characterize events that must be considered in the design.

For engineering purposes the magnitudes are approximate indices of the size of the earthquake; the local magnitude gives a measure of the strength of shaking and M_S indicates the area that might be affected by strong ground motion. In earthquake engineering practice, it is customarily assumed that two earthquakes having the same magnitude will have similar characteristics, including ground shaking, other things being equal; but it should be kept in mind that other things (tectonic setting, depth of rupture, rock type, fault mechanism, rate of activity, etc.) are seldom entirely equal.

The adequacy of seismological data for purposes of design depends upon having sufficient earthquakes in the historical record, with magnitudes and locations determined, so that large magnitude events are also included. For example, if the data include only earthquakes having $M_L < 5$ the probability distribution for large earthquakes would not be defined and it would be of questionable reliability to extrapolate to the probability of earthquakes $M_S > 8$. Lacking sufficient data to define a probability distribution, it is customary in U.S. practice to assume a distribution for magnitudes that is consistent with the seismic history of California, even though this introduces a degree of uncertainty.

In the less seismic regions of the U.S., the seismological data are relatively few and are typically of poor quality. For example, in the eastern part of the country the available historical information on damaging earthquakes seldom includes the instrumentally determined local magnitude of the event but instead gives Modified Mercalli Intensity (MMI) numerals. The MMI index provides information of a lower quality than the magnitude, not only because it is based on personal observations of earthquake effects instead of instrumental records, but also because the actual interpretation is often unreliable.

GEOLOGICAL DATA

The seismic history of the United States, about one to three hundred years depending on location, is a relatively short time for assessing the frequency of earthquake occurrence. For reliable statistical studies to be made, the duration of the seismic history should be long compared to the average time between large earthquakes, a time which appears to range from as short as about one hundred years to several thousand years, depending on the degree of activity of the region. For example, major earthquakes away from continental margins, such as have occurred in central China and the central United States, appear to have the longest recurrence intervals.

The relatively short-time information provided by seismological history can be supplemented by geological information about long-time tectonic processes that are measured in thousands or hundreds of thousands of years. For example, faults that can be identified as having experienced slip during the past hundreds, thousands, or tens of thousands of years provide information about the seismic hazard of a region, but it is a difficult scientific problem to quantify this information.

In the best cases, the geological evidence will be sufficient to establish the length over which a fault has ruptured, the amount of cumulative fault displacement, and information about the period of time over which the movements have taken place. In addition, it is sometimes possible to make inferences concerning whether the fault has moved once, a few times, or many times during its active history. For faults that are active up to the present, geological data such as this can be used to help estimate the magnitudes and frequency of occurrence of earthquakes that may reasonably be expected in the future. It is equally useful if the geological data can be used to rule out the expectation of a specific fault generating an earthquake, which is an extremely important point for faults that may traverse or pass near the site of a critical facility and could pose a hazard both from shaking and fault displacement. If it can be demonstrated that the near surface geological materials are undisturbed, this is conclusive evidence that the fault has not ruptured (and thereby generated an earthquake) since the formation of the oldest undisturbed material. Depending on the age of material and the critical nature of the facility under design, the lack of movement over an established number of years may eliminate the fault from further consideration in formulating the design criteria. For most ordinary construction, a fault that has not moved in Holocene times (the last 11,000 years) can be considered inactive, whereas for the design of nuclear plants, it has been ruled that a fault that has moved once in the last 35,000 years or more than once in the last 500,000 years must be considered as a possible source of future earthquakes.

Depending on the geological data and the judgment of the geologist, various procedures have been employed to interpret the seismic hazard posed by a given fault. The crudest approach is that which simply assigns a maximum size to the earthquake that the fault can generate. This earthquake is variously known as the Maximum Capable Earthquake, Maximum Credible Earthquake, Safe Shutdown Earthquake, Contingency Level Earthquake, etc. For example, a fault whose discernible length is approximately 40 miles might be assigned a Maximum Capable Earthquake (MCE) of $M_s = 7$, or one with a discernible length of 15 miles might be assigned a MCE of $M_s = 6.5$. The MCE represents a "worst case" situation and by itself is not a very informative number, for it does not distinguish between a fault that will have events of the approximate size of the MCE once per 200 years and one for which the return period is once in 500,000 years, even though this information would be very important to engineers preparing seismic design criteria.

SEISMOLOGICAL AND GEOLOGICAL INFORMATION REQUIRED FOR DESIGN

Geological and seismological consultants should address the question of probability of occurrence. A report that merely states "the recommended design earthquake is a Magnitude $M_s = 7.5$ at a distance of 20 km," is incomplete because it gives no indication of the frequency of occurrence of the earthquake. In addition, the geoscientist has made a decision about engineering design which is outside his area of competence. The expertise of geological and seismological consultants is related to geologic and seismic hazards, and their reports should describe the possible earthquakes together with estimates of probability of occurrence, or the possible intensity of ground shaking together with its estimated probability of occurrence. The incorporation of the information into the design criteria should be the responsibility of persons who understand engineering design and the performance of structures, and who can balance the hazard posed by earthquakes with that posed by other problems such as flooding and extreme winds.

A seismological report on a site will usually contain an estimate of the frequency of occurrence of earthquakes within a specified region. For a large, relatively seismic, region, such as the state of California, a rather good estimate can be made because of the large number of historical earthquakes.

For smaller regions within California, or less seismic regions, the historical record of earthquakes may contain so few events that estimates will be unreliable. Usually it is assumed that the distribution of earthquakes of various magnitudes within a region is similar to the distribution for California, and the California distribution is scaled to fit the historical record of the region. This might be described in the report by saying that N earthquakes of magnitude M, or greater, are expected in a 100 year period, and this would be sufficient for constructing the frequency distribution. For some regions of low seismicity it can be assumed that the probability of occurrence of very large earthquakes is negligibly small, but for other regions it may not be easy to decide whether or not the probability is negligible.

Strong motion accelerograms recorded in the past illustrate the kind of ground motions to be expected in the future, and the ground motion to be considered in the design can be described by three components of ground acceleration which are consistent with recorded accelerograms. The recommendations of an earthquake consultant should, preferably, present ground accelerations in the form of appropriate recorded accelerograms from particular earthquakes, or synthesized accelerograms that have appropriate intensity, duration, and frequency characteristics.

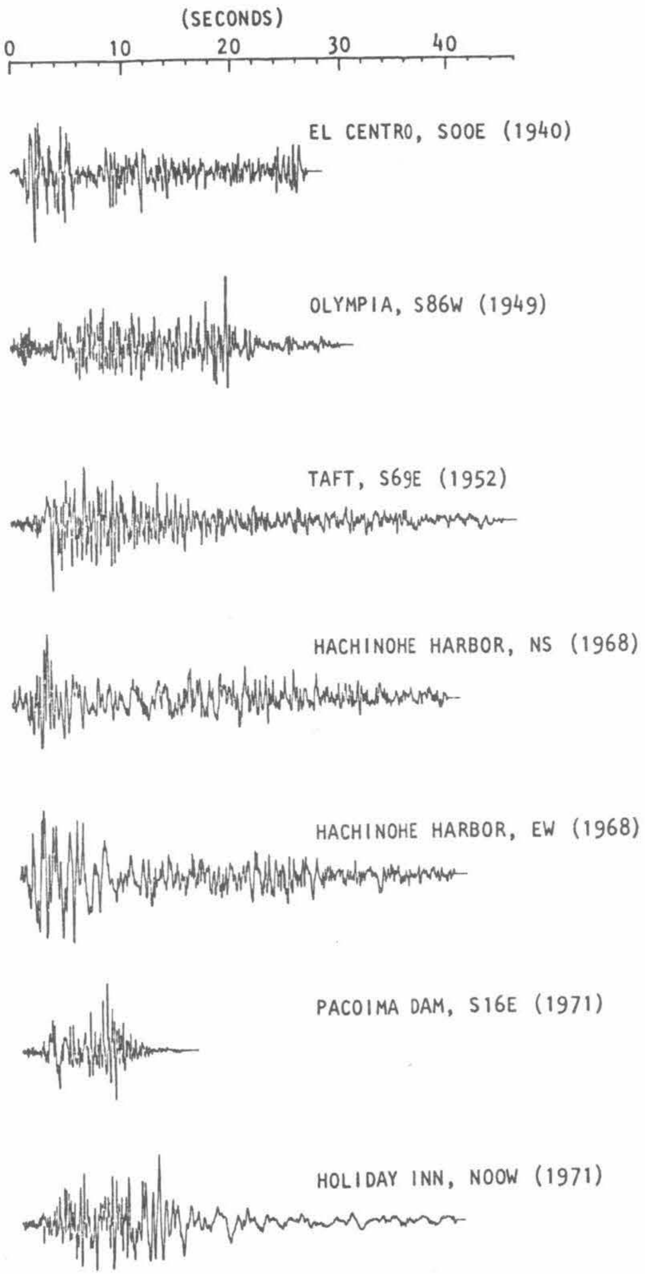
The frequency of occurrence of strong shaking can be specified using the return period which is the average time between earthquake motions of a specified strength or greater. The probability of an occurrence in any one year for an event with a return period R is 1/R, and this can be used to calculate the probability of the occurrence in a longer period of time. For example, the probability of experiencing the shaking with a return period of 100 years in a given 100 year period is found by considering the probability of having at least one such shaking, and the probability of going through the entire 100 years without experiencing the event. These two probabilities cover all possibilities and must therefore add to unity, and since the probability of escaping the 100 year earthquake in one year is 0.99, and for two years is (0.99)(0.99), etc., we have the equation

$$P_{100} = 1-(0.99)^{100} = 0.63$$

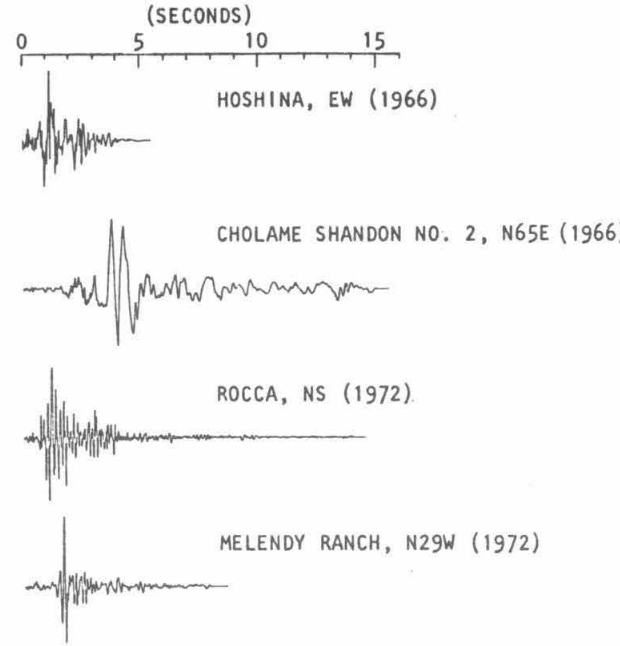
where P_{100} is the probability of occurrence of one or more ground motions with an average return period of 100 years, in a given 100-year period. With a 37% probability (that is, $0.99^{100} = .37$) of not having an earthquake, $P_{100} = 0.63$, i.e., there is a 63% chance of experiencing the 100-year event in a given 100-year period (some 100 year periods may experience 2 or 3 such events).

Often the intensity of ground shaking is described by giving a value of peak acceleration, but by itself this is an ambiguous and oversimplified description, for two ground motions having the same peak acceleration can have appreciably different intensities so far as structural response is concerned. (See the accompanying figures). A related problem occurs when the seismologist or geotechnical consultant describes the ground motion by recommending a smooth "design spectrum," often tied to an estimate of the peak ground acceleration or an "effective acceleration." To take these concepts literally is a mistake. A "design spectrum" is not the same as a response spectrum of actual ground motion or a smoothed "average spectrum," and it is precisely this difference that involves engineering judgment. In addition, there is not yet a clear, accepted definition of "effective acceleration." The concept arises because of the poor correlation between peak acceleration and the actual response of structures.

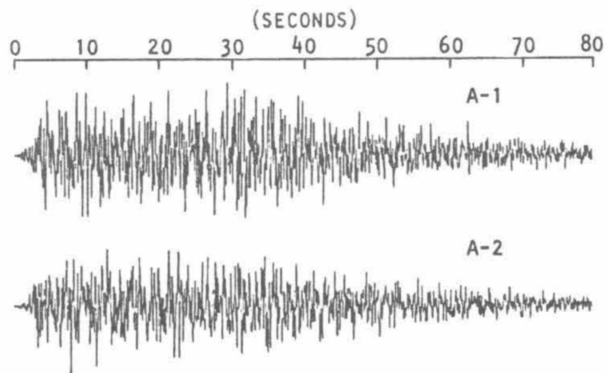
The key step is setting the earthquake design criteria is fixing the level of a smooth design spectrum. The relation of the design spectrum to the response spectra of the expected motions of the design earthquake, or earthquakes, depends on the probability of occurrence of the events under consideration and the degree of conservatism needed for the project. If the structure to be designed is highly ductile and ductile response is acceptable, the design criteria can be set at a significantly lower level than the response spectra of the expected motions. On the other hand, where essentially linear response and a high degree of conservatism are required, the design spectrum may be set well above the response spectra of the expected motions. In most major projects, the appropriate level of conservation is determined in a pluralistic manner with inputs from the owner, concerned regulatory agencies, earthquake engineers and geoscientists.



(a)

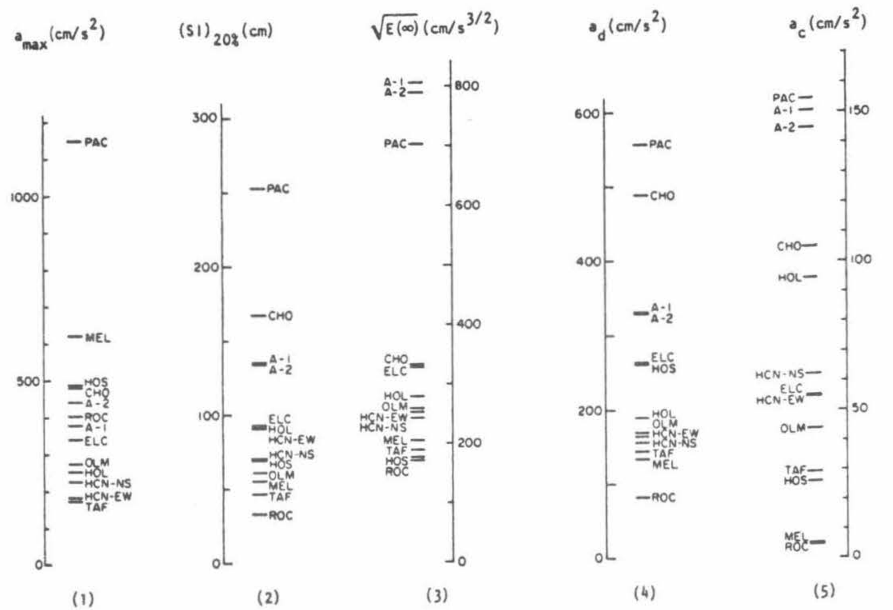


(b)



(c)

Accelerograms from different earthquakes. Group (a) shows accelerograms from $M_s = 6\frac{1}{2}$ to $7\frac{1}{2}$ earthquakes. Group (b) includes records obtained close to the fault in smaller earthquakes, plotted to a different time scale. The much longer records in group (c) are artificially generated accelerograms modeling the expected ground motion close to the fault in a great ($M_s = 8+$) earthquake.



ABBREVIATIONS

ELC	:	EL CENTRO — 1940, S00E
OLM	:	OLYMPIA — 1949, S86W
TAF	:	TAFT — 1952, S69E
HCN-NS	:	HACHINOHE HARBOR — 1968, NS
HCN-EW	:	HACHINOHE HARBOR — 1968, EW
PAC	:	PACOIMA DAM — 1971, S16E
HOL	:	HOLIDAY INN — 1971, N00W
HOS	:	HOSHINA — 1966, EW
CHO	:	CHOLAME SHANDON NO. 2 — 1966, N65E
ROC	:	ROCCA — 1972, NS
MEL	:	MELENDY RANCH — 1972, N29W
A-1	:	JENNINGS-HOUSNER-TSAI, TYPE A-1
A-2	:	JENNINGS-HOUSNER-TSAI, TYPE A-2

Ratings of accelerogram strength by different measures of the intensity of shaking. The accelerograms are identified in the list of abbreviations and are plotted in Figure 21. The measurements of intensity used are explained in the text. Note the change in rankings of the records according to the different measures. No single-parameter measure of strength of shaking has proved completely satisfactory; measuring strength by peak acceleration, though commonly used, is not entirely satisfactory.